Controlling Cryogenics for Creating Mars Environment

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Abstract

Kennedy Space Center has activated its first operational Mars environmental simulation process, the Mars Electrostatic Chamber (MEC). The chamber has been designed to provide for research and testing relative to future missions to Mars. Environmental characteristics of Mars have been replicated, including temperature, pressure, and atmospheric composition. Integration of existing and newly acquired hardware with a centralized controller was performed to bring about successful near-autonomous operation.

The MEC is fundamentally comprised of pressure, atmospheric, and temperature control systems. The temperature control system is used to replicate temperatures within actual minimum and maximum values as would be experienced on Mars. A liquid/gaseous nitrogen supply was used to obtain this temperature range, as well as various heating techniques. Fundamental to the stabilization of temperature within the chamber was the optimal control of extremely cold nitrogen. After incessant testing and characterization, significant cooling implementation design changes, and controller instrumentation modifications, this cryogenic supply was successfully manipulated by a programmable controller system with appropriate programming.

Introduction

The Mars Electrostatic Chamber (MEC) was designed to perform research and testing in preparation for the Mission to Mars. The chamber is utilized to simulate limited atmospheric conditions as experienced on the planet. The MEC is expected to potentially endure lengthy tests, and due to the complexity for controlling such an environment, Kennedy Space Center (KSC) personnel have deemed it beneficial to develop an automated control system for this chamber. In addition, a manual control panel has been developed to add more flexibility to the chamber as an alternative to the graphical user interface (GUI). This panel allows experimenters to operate the chamber in such a way that enables them to select individual settings and perform manual tests, while still maintaining the safety associated with an automated system. The MEC primarily consists of three major systems: pressure control, atmospheric control, and temperature control. The pressure control system is used to lower the pressure of the chamber to that of the Martian atmosphere. The atmosphere control system is utilized to monitor and maintain the gasses contained within the chamber as desired. The temperature control system is used to replicate temperatures experienced on Mars. In part due to the high thermal transfer characteristics of cryogenic nitrogen, achieving the desired temperature controllability required extensive testing and chamber characterization.

Chamber Physical Description

The MEC is 7 feet in length, nearly 4 feet in diameter, and has a volume of 52 cubic feet (Fig. 1). Access ports are provided for component and peripheral device feed-though. In addition, ports are used for existing pressure measurement, temperature signal lines, and gas feed-throughs. Access ports are also provided for the purpose of monitoring payloads. The inside of the chamber has been fitted with a cooling shroud that surrounds the back, sides, and top of the chamber volume. Located in the bottom of the chamber is a deck on which experiments are placed. [1]

Figure 1. Mars Electrostatic Chamber

Chamber Systems

Pressure Control System. The pressure control system is used to regulate the pressure within the chamber using two pumps: a primary and a backup secondary. A single throttle valve is used to control the rate of depressurization and also to regulate the rate of chamber repressurization. A pressure controller is used to operate the throttle valve and provides control when approaching the desired pressure setpoint. Two sets of capacitance manometers are used to measure the actual pressure within the chamber in order to provide the safety of having redundant measurements.

Atmosphere Control System. The atmosphere control system serves two major functions: gas analysis and gas replenishing. Analysis of the chamber atmosphere is performed by a residual gas analyzer via a capillary tube. The readings are then sent to the GUI and displayed on the screen. Gas replenishing consists of a mass flow valve and its controller. The PLC is used to control the mass flow controller, which in turn is used to manage the amount of atmospheric gas that is introduced into the chamber.

Initial Temperature Control System. The project began with the continuation of previous work done by others. There was an existing, or initial temperature system, as shown in Figure 2 that utilized both heating and cooling. The heating portion consisted of a series of tape heaters placed around the chamber. A standalone controller determined the operation of each heater. The heaters were used to trim the temperature at a desired level and to attempt to assist the nitrogen in obtaining a stable predetermined temperature. The heat exchanger consists of a capillary system that incorporates the door, deck, and interior shroud of the chamber. The shroud is composed of two sheets of stainless steel welded together in such a fashion that it creates passageways for flow.

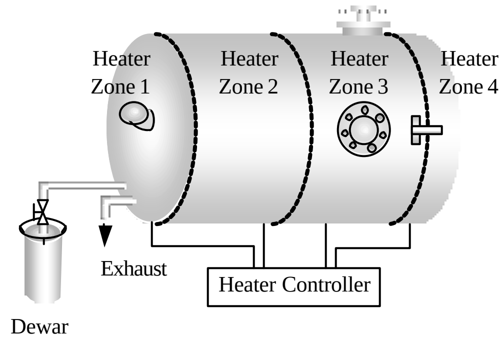

Figure 2. Initial Temperature Control System

The cooling portion of the temperature system used gaseous nitrogen vented from the top of a liquid nitrogen dewar. This potentially allowed some area temperatures within the chamber to drop to nearly –300 degrees Fahrenheit during cooling. The only method of controlling the amount of coolant into the system was to manually adjust the valve on the top of the dewar.

There were no existing means for measuring the temperature of the cooling system or any area inside the chamber, except for the use of individual standalone temperature measurement devices. Data cables had to be routed through existing feedthroughs to accomplish temperature measurement. The achievement of desired temperature was based upon manual measurement, observation, and manual corrective action. Initial tests indicated more than a 300°F temperature differential between various cooling zones within the chamber (Fig. 3). This differential was determined to be caused by the extremely low temperature of the nitrogen and the lack of flow control. This ultimately hindered the thermal transfer characteristics of the cooling configuration. It was at this point it became clear that an innovative means of adequately controlling the cooling system would have to be developed.

<u>Final Temperature Control System</u>. After many tests, iterations of hardware configurations, and various approaches of control strategy, a configuration was created and tested that proved to operate within the established criteria (Figure 4). The configuration consists of two dewars of LN_2 connected in tandem to the system. Gaseous nitrogen (GN_2) is drawn from the top of the dewars to supply the cooling medium. Two solenoid valves are used to select which dewar is to be used at a given time, which provides for continuous flow even when one dewar is being changed or serviced. The cryo is mixed with warm GN_2 from the building supply that has flowed through the warm GN_2 heater to create nitrogen that is warm enough to not cause the CO_2 in the chamber to condensate, or accumulate dry ice. In addition, the warm GN_2 is used to assure that all nitrogen entering the chamber has been evaporated into a gaseous state. The GN_2 flow is measured with a turbine flow meter and controlled with an analog cryo control valve.

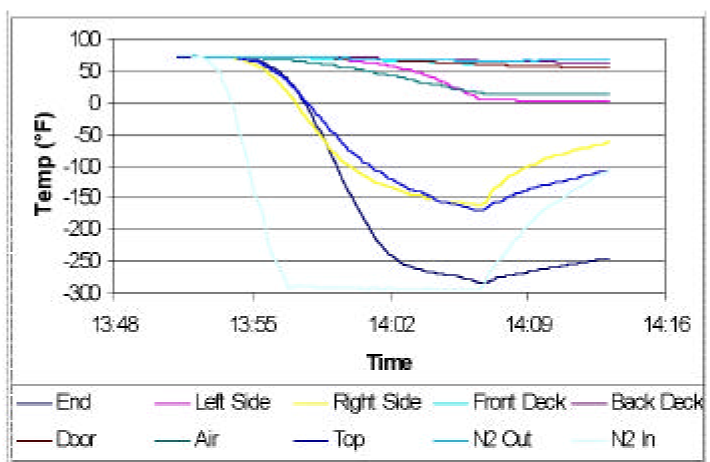

Figure 3. Initial Cooling Test Results

Cooling is fed into the preexisting chamber shroud via a single input line and flow is

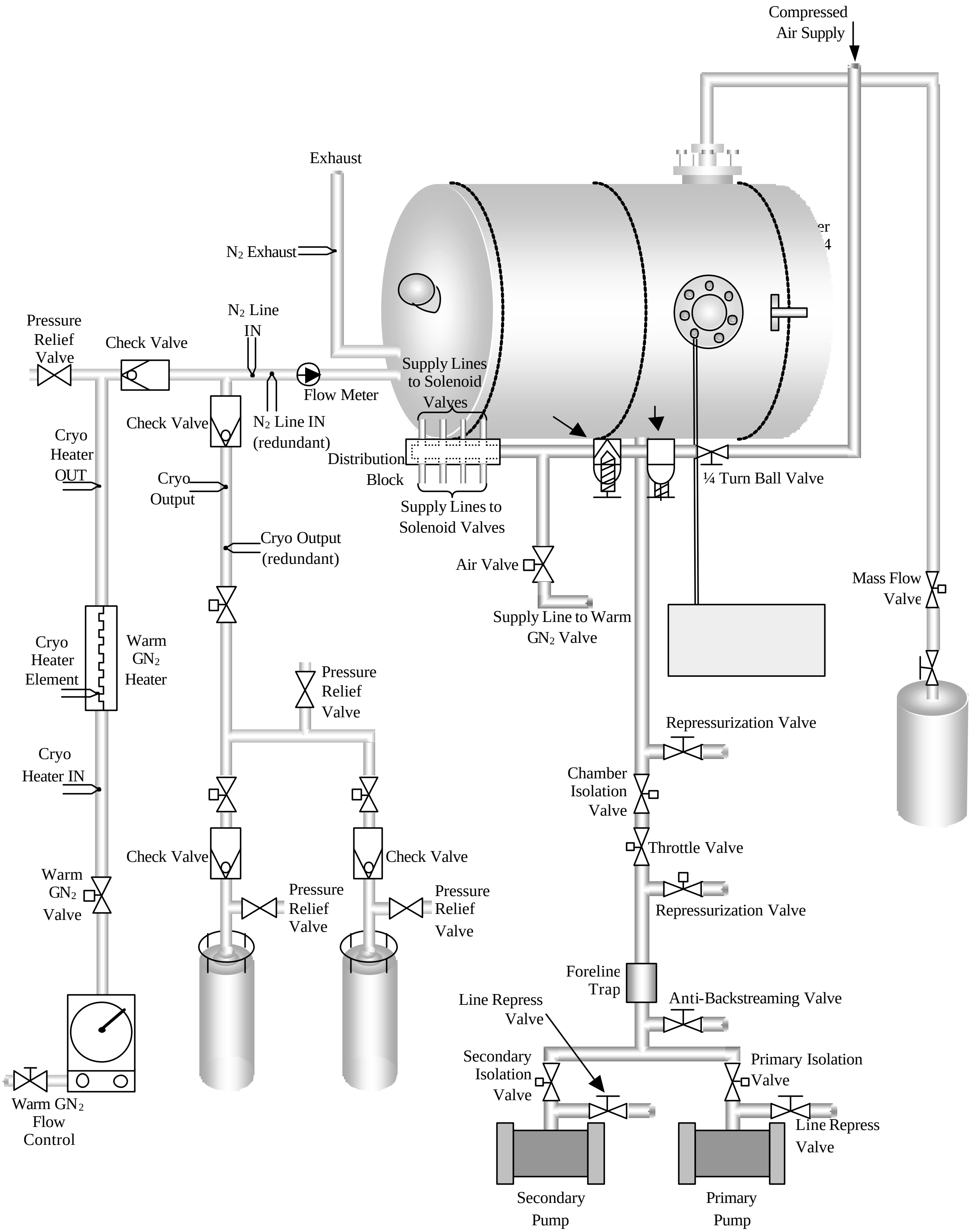

Figure 4. Final System Configuration

divided into different regions of the shroud through various branches of cooling line arrangements. The GN_2 then egresses through the exhaust manifold and is vented through the piping to the exterior of the building. The shroud is comprised of eight zones and each zone is supplied cooling fluid in either a series or parallel arrangement, as depicted in Figure 5.

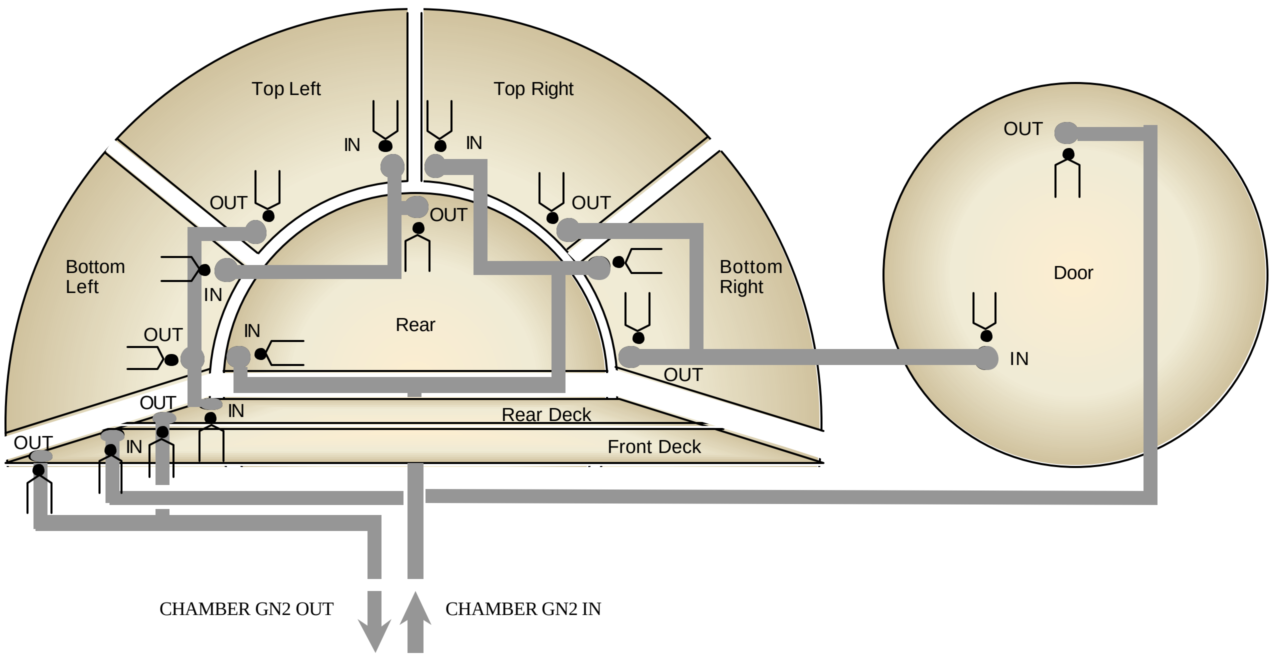

Figure 5. Cooling Shroud Zones and Thermocouple Placement

Heating System. In order to heat the chamber, a combination of warm GN_2 routed through the warm GN_2 heater and tape heaters are used. There are sixteen tape heaters located in four zones throughout the length of the chamber. The tape heaters may be used to help maintain a desired temperature throughout the chamber, and to return the chamber to ambient temperature following an experiment. Warm GN_2 flows from an existing supply line in the room and through an adjustable regulator flow control. An in-line heater is used to heat the ambient GN_2 in order to decrease the time it takes to return the chamber to ambient temperature and to provide satisfactory temperature control. The warm GN_2 line is adjoined with the cold GN_2 line before being metered and throttled by the flow meter and the analog cryo control valve, respectively, prior to entering the chamber.

Temperature Measurement System. There are a total of forty-eight thermocouples used for temperature measurement for the chamber. Twenty of these are located in heater zones near the tape heaters. These twenty thermocouples are connected in parallel such that they are averaged into four temperature measurements (one per zone). In order to obtain accurate indication of the cooling process and its consequent effect on the chamber, it was necessary to acquire more temperature readings. A total of 28 additional k-type thermocouples for monitoring and controlling the temperature of the MEC were permanently installed. Of these 28 thermocouples, 8 are located in the cooling lines outside of the chamber, 16 are located on the input and output pipes of each zone of the shroud (Fig. 5), and 4 are thermocouple probes located near the proximity of the payload.

There are eight thermocouples located external to the chamber. Two thermocouples are located in the GN_2 input line to the chamber, and another one is located in the exhaust line. There are three thermocouples associated with the cryo heater: one at the input, one on the heating element, and one at the output. There are two additional thermocouples located in the cryo GN_2 line to monitor the temperature of the cold GN_2. All of the thermocoup les are k-type, with the exception of the twenty zone thermocouples that are t-type. These thermocouples are intrusive and located within the interior of the pipes, to obtain the most accurate measurement.

The 16 thermocouples inside the chamber are attached to the pipes at the inlet and exhaust port of each shroud zone using stainless steel clamps. These thermocouples are used to monitor the temperature differential of each zone to determine real-time cooling rate and to assure the preclusion of violating to low temperature limits.

Four flexible thermocouple probes are mounted inside the chamber so they can be arranged to monitor the atmospheric temperature close to, but not in contact with the chamber payload. These thermocouples are used to monitor the temperature that the payload is exposed to, and also for indication and verification of thermal transfer to the chamber's atmosphere.

Cooling Tests

Before specifying the cooling system needed for the MEC, it was necessary to characterize the chamber and the cooling system. Many cooling tests were performed using various hardware configurations to determine the best cooling method for this particular chamber.

LN_2 Temperature Verification. It was deemed prudent to verify the coldest practical temperature obtainable from an LN_2 dewar prior to beginning the actual cooling system tests. The coldest consistent temperature obtained was -320°F, as anticipated. It was therefore verified that the dewars would be able to provide cooling fluid at a temperature that was potentially low enough to serve as the cooling means for the MEC. Additionally, it was apparent that the control system would have to be cognizant of the extremely low temperature of the medium it would be manipulating.

Short Duration Test. With an acceptable hardware configuration and control strategy established, the cooling system was tested at various setpoints for its ability to achieve and maintain a constant desired temperature. A short duration test output for the setpoint of -150°F is shown in Figure 6. As can be seen from the graph, although the temperature of the cryo supply and the cooling input fluctuate (lower two responses), the temperature of the coldest zone (third plot from bottom) is relatively stable as it approaches the setpoint. The chamber atmospheric temperature is shown to steadily decline by the top response line.

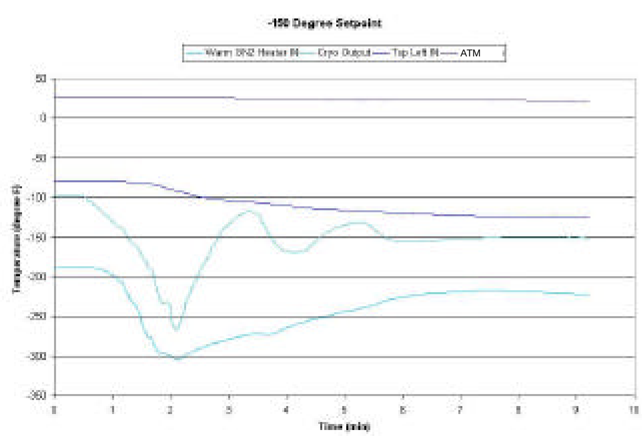

Figure 6. -150 °F Cooling Test

Long Duration Test. A long duration test output for the setpoint of -190°F is shown in Figure 7. The bottom line shows severe fluctuations in the temperature of the cryo output from the dewar. Above that, similar fluctuations may also be noted in the temperature of the cooling line input to the chamber after being mixed with warm GN2. However, the next graphed line above, which represents the lowest temperature surface within the chamber, is held constant once recovering from initial cryo shock. Most importantly, the top graphed line response of atmospheric temperature maintains a steady approach to the desired setpoint, despite serious cryo fluctuations.

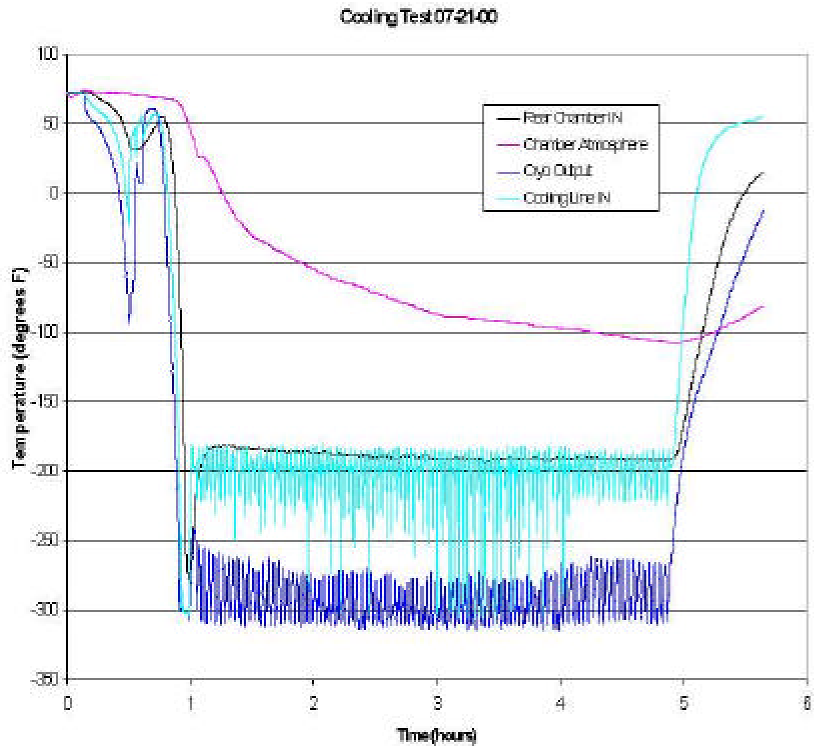

Figure 7. –190 °F Cooling Test

Additional Considerations

The pressure, atmosphere, and temperature systems were coalesced into one accordant system to provide the desired chamber operational characteristics. Physical/mechanical integration was performed, as well as software implementation and programming. Fundamental to the successful operation of the temperature control system, was the seamless integration of all hardware and software, including the PLC and GUI programming.

System Integration. Electrical and signal integration was conducted throughout the implementation process. Electrical integration included the distribution of electrical lines to all devices requiring power. Since various levels and forms of electrical power were necessary, a master plan was developed to determine overall voltage, current, and signal type requirements. Control and signal lines external to individual components were routed to the PLC. The PLC collects all measured and monitored data, applies this information to its programmed instructions, and thus updates all outputs accordingly.

Hardware Configuration. Instrumentation of hardware for the MEC is facilitated by centralization of connection with a PLC. The PLC accepts inputs from the manual control panel, capacitance manometers, flow meter, pressure controller, cooling line thermocouples, cooling shroud thermocouples, and chamber atmospheric thermocouples. In addition, numerous inputs are received from the virtual panel. The PLC provides outputs to the manual control panel indicators, vacuum system, heater system, automated sequence hardware, atmospheric gas valve, alarm, pressure system outputs, warm GN_2 valve, pressure system displays, and cryo system outputs. Numerous outputs are sent to the virtual GUI panel.

Software Configuration. Software was required to program and to allow the various computerized components within the sytem to function. The PLC required its own software, as well did some of its smart modules. Specifically, the ASCII BASIC PLC module was programmed with its own software to provide communication between the PLC and the pressure controller that controlled the throttle valve for pressure stabilization. In addition, other separate components required their own software and programming, such as the residual gas analyzer (RGA) and the GUI. The GUI virtual instrumentation interface is administered on separate computer with a separate operating system.

PLC Program. Process devices used to interface with the MEC such as the manual control panel, capacitance manometers, flow meter, cooling line thermocouples, cooling shroud thermocouples, and chamber atmospheric thermocouples are connected to the PLC. Each device is continuously read to obtain current values. These values are then stored to a specific register for that device. Means to control connected inputs and outputs are incorporated into the PLC program. As a result of the complexity of the control process, many different types of PLC modules were needed to achieve desired operation. In the end, 84 discrete, 8 analog, and 32 thermocouple inputs and outputs composed the total I/O system. Proportional Integral Derivative (PID) methodology was used to control the cryo valve according to the temperature of the input nitrogen. The flow of the warm GN_2 is for all intents and purposes considered a constant.

GUI Program. A graphical user interface was created with soft controls and indicators similar to those on the physical control panel, with the addition of elaborate graphical management capabilities. Each virtual instrument program consisted of a graphical program, or diagram, and a graphical user panel. Although some of the functions of the GUI were redundant, many additional functions were made possible by its accretion. Additional programs were created to oversee system functions such as vacuum, temperature, data recording, alarms, and system setpoint control, monitoring, trending, charting, and graphing functions. All temperature control parameters were made to be user-selectable from the GUI, including the capability to override default values.

Simplified Operational Overview

An automatic sequence begins by the primary pump starting, and the primary isolation valve opening (Fig. 4). The pressure controller opens the throttle valve, and the chamber is evacuated to 600 millitorr. The mass flow valve is then opened to begin backfilling the chamber with atmospheric gas. When the pressure reaches 7 torr, the cooling sequence can begin. Cryo isolation valves 1 and 2 are opened, and then the analog cryo control valve is opened. The warm GN_2 valve is also opened so the two gasses can begin to mix in the cooling lines to create nitrogen at the appropriate temperature for the MEC. The flow rate of the mixed GN_2 is monitored with a flow meter just before it enters the chamber.

The pressure, temperature, and atmospheric content are monitored and maintained automatically by the system throughout the duration of the test. There is the opportunity for user involvement, but it is not necessary. The chamber can run autonomously for any length of time that the LN_2 dewar and atmospheric gas supplies are provided.

When the experiment is finished, the program will run the automatic shut down sequence to return the chamber to ambient temperature and pressure. The atmospheric gas flow is halted. Cryo isolation valves 1 and 2, and the cryo control valve are closed while the warm gas continues to flow through the shroud. The warm GN_2 heater is turned on to heat the warm GN_2 gas. The tape heaters are activated in all four zones to assist the warm GN_2 heater in warming the chamber. Once the temperature reaches room temperature, the primary isolation valve is closed and the primary pump is deactivated. The automated repressurization valve is then opened and the throttle valve is used to control the rate of repressurization of the chamber.

Conclusions

The Mars Electrostatic Chamber has undergone extensive modifications and upgrading. The chamber has been enabled to perform testing at conditions similar to those found on Mars, in terms of pressure, temperature, and atmospheric content. Considering no cryogenic testing had been performed on the chamber previously, it may be considered fortunate that the development team has equipped the chamber with elaborate cryogenic cooling capabilities. The original configuration produced many problems, such as the flow from the dewar wasn't solely gaseous nitrogen. Instead, it was a mix of gaseous and liquid nitrogen, which is undesirable. Another issue with this arrangement was the inconsistent flow of nitrogen regardless of valve position. This made it virtually impossible to operate the chamber at a steady temperature for any period of time, and thus impossible to achieve an resemblance of even crude temperature control.

First encounters with the chamber revealed that it was not designed from conception as one integrated Mars simulation chamber. Investigations indicated that the chamber was purchased in fragments, and various components were foraged to make the system somewhat functional. [2] This proved to provide for a challenging implementation process since it mandated the interfacing of components that were not designed to be interfaced with on a system level.

Testing demonstrated the ineffectiveness of the cooling shroud to serve as a consistent cooling mechanism. Multiple zones connected in series combined with undesirable flow patterns gives the chamber high temperature gradients and less than ideal heat transfer. Development and integration of a new heat transfer apparatus inside the chamber could improve upon the shortcomings of the current arrangement.

A potential area of development for the chamber is the possibility of creating a cooling system based upon the recirculation of cryogenic fluid. Recirculation would provide a means of obtaining the required heat exchange while at the same time conserve cryo. Conserving cryo not only would save money but also would result in the operator not having to change cryo supplies as often.

Other potential improvements in the cooling system may include the development of a cryogenic generation system. Since obtaining, installing, and removing liquid nitrogen dewars are labor intensive and time consuming tasks, it would appear prudent to investigate the production of cryo at the chamber. Since ambient temperature GN_2 is available for chamber use, it could be refrigerated before entering the chamber. Such a system could be developed and are available commercially.

Cooling tests were performed to determine the characteristics of the chamber and to assist in the development and implementation of a control scheme by which the cryo could successfully cool the chamber. The erratic nature of the flow from the dewar hindered the PID loop tuning process. To properly account for this problem, many cooling tests, characterization processes, and changes in hardware and instrumentation configurations were performed. The ultimate mixture of warm GN_2 and cryogenic GN_2, coupled with PID control of the cryo control valve, resulted in successfully controlling the temperature of the GN_2 entering the chamber at every chamber temperature setpoint that was attempted. The finalized system is capable of cooling down to the freezing point of $C0_2$ at 7 torr, and has been proven to maintain the controlled variable at an essentially constant setpoint value.

The Mars Electrostatic Chamber has been upgraded to the extent that it is now a fully functional Mars simulation development chamber. The chamber has been enabled to perform testing at conditions similar to those found on Mars, in terms of pressure, temperature, and atmospheric composition. However, further testing and improvements should be performed to certify its characteristics across all parameters and under all conditions. Additional automated programming could be added to create specific simulation scenarios. Once full testing is performed and follow-up modifications made, the chamber will then be ready to have its capabilities fully utilized. Through more research, development, and testing, it will prove to be far more capable than once thought possible, and in actuality, it has accomplished that already.

References

[1] Buchanan, Randy K., Aubri Barnett. (2000). Mars Electrostatic Chamber Operations Manual. Unpublished manuscript, NASA Kennedy Space Center, FL.

[2] Personal communication with Dean Lewis, Aerospace Technologist, NASA Kennedy Space Center FL. June 13, 2000.